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DACTYL ORBIT DETERMINATION ANALYSIS

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Galileo's recent discovery that the asteroid Ida has a satellite (now known as Dactyl) has allowed, for the first time, an accurate estimate of an asteroid's bulk density. Dactyl and Ida appear in 47 images returned from the Ida encounter. The locations of Ida and Dactyl in these images were used to estimate Dactyl's orbit as a function of Ida's mass. Interestingly, a wide range of possible orbits fit the observational data equally well. Dynamical and statistical arguments are used to constrain the range of possible orbits and hence the mass (and density) of Ida.

INTRODUCTION

The discovery of Dactyl by the Galileo spacecraft is the first direct observation of a satellite orbiting an asteroid. This discovery supports the theory that satellites orbiting asteroids may be a commonplace occurrence (Ref. 1). In the Solid State imaging (SSI) data returned from the Ida encounter, both Dactyl and Ida appear in 45 images, and two additional images contain Dactyl alone. The locations of Ida and Dactyl in these images provide information that can be used to estimate Dactyl's orbit and Ida's density, which is of great interest because it gives a strong indication of Ida's composition (Ref. 2). While Dactyl's orbit is of inherent interest, the greatest significance of knowing the orbit is that it provides a value for Ida's density.

Initial attempts to apply classical astronomical orbit fitting methods to determine a preliminary estimate for Dactyl's orbit, assuming a reasonable value for Ida's density, did not produce the desired results because of numerical problems, which, it was later realized, were caused by the fact that the line of sight from Galileo to Ida lay nearly in the plane of Dactyl's orbit for most of the images. The SSI Team then requested assistance from the Navigation Team in order to apply more sophisticated orbit determination methods to solve the problem. The authors thus became. involved in an unexpected orbit determination task that was both challenging and enjoyable.

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PROCEDURE

Objective and Method

The objective of this study was to determine *preliminary* estimates for Dactyl's orbit and Ida's density. To this end, the analysis was simplified by assuming that Dactyl's orbit was Keplerian (i. c., a two-body conic) and that Ida's gravitational potential behaved as if Ida were a spherical body of uniform density.

The approach taken was to apply a least squares differential correction technique to the problem. The orbital elements of Dactyl were iteratively adjusted until the weighted sum of the squares of the errors in the right ascension (RA) and declination (DEC) of Dactyl in each image was minimized. Various assumptions about the uncertainty or weight to be associated with each observation were investigated and it was found that the effect on the resultant solutions was relatively minor. The weights which were used for the results presented below ranged from an uncertainty of about 1 pixel (~2 km) for the earliest pictures to about 10 pixels (~1 km) for the latest pictures which included both Dactyl and Ida. These weights account both for the variation in the spatial resolution of the pictures over this time span (from ~2.4 km/pixel to ~.087 km/pixel), as well as the uncertainties associated with the shape and center of mass modeling for both Ida and Dactyl.

Data Reduction

The analysis involved in reducing the raw data associated with the images (exposure time, camera pointing (RA and DEC) and twist*, coordinates of Ida and Dactyl, estimated accuracy of these coordinates, etc.) is described in Ref. 1. A tots! of 47 independent images were used, 45 of which contained both Ida and Dactyl providing highly accurate relative positions and 2 additional images containing only Dactyl. Table 1 includes the measured positions of Dactyl and Ida and the camera pointing data for the images. The measured positions for the centers of mass for Dactyl and Ida were determined by fits of the shape models described in Ref. 3 to the bright limb when appropriate. Several independent measurements were made and combined to produce Table 1 (Ref. 1). The internal consistency was better than ~0.5 pixel.

* Same as "camera North azimuth" defined in Table 1.

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FORMAT FOR TABLE 1 — ... data ... Ex...

TABLE 1

Measured positions of Dactyl and Ida and Camera Pointing

Image #	Time to Encounter[1] (min.)	Range[2] (km)	Camera RA[3] (deg)	Camera DEC[3] (deg)	Camera North AZ[3] (deg)	Dactyl Line[4]	Dactyl Sample[4]	Ida Line[4]	Ida Sample[4]
202530700	323.58	240,418	-167.184	-4.100	92.653	383.5	408.7	388.9	447.4
202539900	230.57	171,315	-167.146	-3.877	93,005	388.6	387.6	396.7	437.2
202540000	229.55	170,562	-167.139	-3,864	93,010	372,3	377.5	380.4	427.2
202540100	228.54	169,811	-167.139	-3.848	93.016	350.5	>379.0	358.4	429.0
202540145	228.04	169,434	-167.143	-3.871	93.016	394.5	383.4	402.6	433.4
202542200	207.31	154,037	-167.129	-3.770	93.142	356.5	377.6	365,3	431.3
202544500	184.05	136,762	-167.119	-3.668	93.312	372.6	383.6	382.5	440.6
202546800	160.80	119,483	-167.090	-3.509	93.532	344.5	364.2	355.6	425.8
202546900	159.79	118,736	-167.094	-3.512	93,543	362.6	372.8	373.6	434.5
202547000	158.78	117,984	-167.099	-3.496	93,554	353.1	382.4	364.6	444.2
202547045	158.27	117,609	-167.088	-3.510	93.559	375.9	363.6	387.4	425.6
202549100	137.55	102,215	-167.078	-3.322	93.828	352.5	383.8	365.0	451.5
202551400	114.29	84,943	-167.027	-3.060	94.240	362.6	353.3	377.0	428.5
202551445	113.78	84,565	-167.035	-3.045	94.251	350.6	371.0	365.1	446.0
202551545	112.77	83,814	-167.034	-3.034	94.273	356.4	371.2	371.0	446.3
202551600	112.27	83,439	-167.024	-3.021	94.284	345.0	357.1	359.5	432.6
202553700	91.03	67,671	-166.972	-2.643	94.876	344.9	350.9	362.3	435.7
202553800	90.02	66,920	-166.982	-2.622	94.910	350.2	372.7	367.6	457.7
202553900	89.01	66,169	-166.979	-2.601	94.943	354.4	372.8	371.6	458.0
202553945	88.50	65,794	-166.969	-2.584	94.963	342.5	357.6	359.8	443.3
202554800	79.91	59,413	-166.937	-2.356	95.305	330.0	352.6	349.0	443.7
202556000	67.78	50,409	-166.885	-1.955	95.937	342.7	351.6	363.8	451.6
202556045	67.27	50,032	-166.878	-1.932	95.969	336.9	346.1	358.0	446.1
202556100	66.77	49,657	-166.876	-1.916	95.998	344.7	346.2	366.0	446.6
202556200	65.75	48,907	-166.866	-1.865	96.066	328.9	339.7	350.5	440.6
202556245	65.25	48,532	-166.879	-1.854	96.099	349.2	364.4	370.9	466.0
202557100	56.65	42,155	-166.803	-1.426	96.755	336.6	328.4	360.4	439.1
202557200	55.64	41,405	-166.793	-1.366	96.848	333.7	325.2	357.7	437.4
202557300	54.63	40,656	-166.788	-1.306	96.939	334.4	329.6	358.3	442.7
202557345	54.13	40,280	-166.792	-1.282	96.989	349.3	341.7	373.5	455.2
202558300	44.52	33,161	-166.681	-0.539	98.115	313.3	316.6	340.4	445.3
202558400	43.51	32,409	-166.676	-0.448	98.266	322.4	327.2	349.6	458.0
202558500	42.50	31,661	-166.667	-0.347	98.421	320.3	335.3	348.1	467.7
202558545	41.99	31,286	-166.645	-0.296	98.499	318.1	308.4	345.6	442.0
202559400	33.40	24,927	-166.489	+0.819	100.234	308.6	288.1	339.5	444.9
202560600	21.27	15.975	-166.060	+3.939	105.037	235.2	256.9	268.5	476.4
202560645-1	20.76	15,606	-166.016	+4.142	105.354	226.4	228.4	262.5	452.1
202560700	20.25	15,232	-166.009	+4.349	105.682	254.8	258.5	288.1	487.1
202560745	19.75	14,862	-165.976	+4.584	106.031	237.5	257.65	270.6	490.7
202561278	14.36	10,927	-165.508	+7.969	111.138	169.2	242.9	192.9	549.8
202561313	14.07	10,719	-165.470	+8.234	111.523	172.6	237.1	195.1	545.1
202561326	13.93	10,614	-165.455	+8.358	111.719	182.6	221.9	204.9	547.4
202561339	13.78	10,511	-165.420	+8.491	111.909	168.1	207.9	189.4	525.9
202561352	13.64	10,406	-165.412	+8.619	112.110	184.7	217.9	205.8	539.4
202561578	11.32	8,742	-165.322	+11.079	115.420	576.0	519.2	578.4	901.6
202562278[5]	4.25	3,957	-161.727	+32.704	139.831	220.2	194.9	-	-
202562700[5]	0.06	2,292.	-104.804	+81.633	209.417	455.6	14.0	-	-

[1] Time of encounter was UTC 1993 **Aug. 28,** 16:52:04.7; [2] **Approximate spatial resolution** (km/pixel) **can be obtained by multiplying by** 10^{-5}; [3] Camera **pointing direction** ~~based on~~ computed from Ida coordinates and **spacecraft ephemeris:** RA=right acsension, DEC=declination, North AZ (azimuth) is measured clockwise **from the line' direction to the projected direction of celestial north**. All **quantities for** J2000 [4] **Adjusted for geometric** distortion (Davies *et al.*, 1994, 1995); [5] **The center of mass of Ida is off the edge of the frame in this image, but the bright limb is imaged and sufficient to locate the position of the Ida shape model.**

Summary of Inputs for Dactyl Orbit Determination

(Data for Table 1) pg 1

Picture	S/C Clock	Time from Reference* (sec)	Time from Reference* (min)	Time (UTC)	Time (ET)	Ida Sample	Ida Line	Ida-2 Sample	Ida-2 Line	Delta Sample	Delta Line	Range to Ida (km)	Camera Pointing (EME2000) RA (deg)	Camera Pointing (EME2000) DEC (deg)	Camera Pointing (EME2000) Twist (deg)	North (deg)
1	202530704	-19415.00	-323.58	11:28:30	11:29:30	447.4	388.9	408.7	383.5	-38.7	-5.4	240418	-167.184	-4.100	87.347	92.653
10	202539904	-13834.00	-230.57	13:01:31	13:02:31	437.2	396.7	387.6	388.6	-49.6	-8.1	171315	-167.146	-3.877	86.995	93.005
12	202540004	-13773.20	-229.55	13:02:32	13:03:32	427.2	380.4	377.5	372.3	-49.7	-8.1	170562	-167.139	-3.864	86.990	93.010
14	202540104	-13712.50	-228.54	13:03:33	13:04:33	429.0	358.4	379.0	350.5	-50.0	-7.9	169811	≤7. 39	-3.848	86.985	93.016
15	202540149	-13682.10	-228.04	13:04:03	13:05:03	433.4	402.6	383.4	394.5	-50.0	-8.1	169434	-167.143	-3.871	86.985	93.016
16	202542204	-12438.50	-207.31	13:24:46	13:25:47	431.3	365.3	377.6	356.5	-53.7	-8.8	154037	-167.129	-3.770	86.858	93.142
17	202544504	-11043.20	-184.05	13:48:02	13:49:02	440.6	382.5	383.6	372.6	-57.0	-9.9	136762	-167.119	-3.668	86.688	93.312
18	202546804	-9648.07	-160.80	14:11:17	14:12:17	425.8	355.6	364.2	344.5	-61.6	-11.1	119483	-167.090	-3.509	86.468	93.532
20	202546904	-9587.20	-159.79	14:12:18	14:13:18	434.5	373.6	372.8	362.6	-61.7	-11.0	118736	67.094	-3.512	86.457	93.543
22	202547004	-9526.50	-158.78	14:13:19	14:14:19	444.2	364.6	382.4	353.1	-61.8	-11.5	117984	-167 [illegible]99	-3.500	86.446	93.554
23	202547049	-9496.20	-158.27	14:13:49	14:14:49	425.6	387.4	363.6	375.9	-62.0	-11.5	117609	-167 [illegible]88	-3.510	86.441	93.559
24	202549104	-8252.70	-137.55	14:34:32	14:35:32	451.5	365.0	383.8	352.5	-67.7	-12.5	102215	-167.078	-3.322	86.172	93.828
30	202551404	-6857.40	-114.29	14:57:48	14:58:48	428.5	377.0	353.3	362.6	-75.2	-14.4	84943	67.027	-3.060	85.760	94.240
31	202551449	-6826.90	-113.78	14:58:18	14:59:18	446.0	365.1	371.0	350.6	-75.0	-14.5	84565	-167.035	-3.045	85.749	94.251
33	202551549	-6766.20	-112.77	14:59:19	15:00:19	446.3	371.0	371.2	356.4	-75.1	-14.6	83814	67.[illegible]34	3.034	≤5.727	94.273
34	202551604	-6735.90	-112.27	14:59:49	15:00:49	432.6	359.5	357.1	345.0	-75.5	-14.5	83439	167.024	-3.021	85.716	94.284
36	202553704	-5461.90	-91.03	15:21:03	15:22:03	435.7	362.3	350.9	344.9	-84.8	-17.4	67671	-166.972	-2.643	85.124	94.876
38	202553804	-5401.20	-90.02	15:22:04	15:23:04	457.7	367.6	372.7	350.2	-85.0	-17.4	66920	-166.982	-2.622	85.090	94.910
40	202553904	-5340.50	-89.01	15:23:05	15:24:05	458.0	371.6	372.8	354.4	-85.2	-17.2	66169	-166.979	-2.601	85.057	94.943
41	202553949	-5310.20	-88.50	15:23:35	15:24:35	443.3	359.8	357.6	342.5	-85.7	-17.3	65794	-16[illegible]69	-2.584	85.037	94.963
42	202554804	-4794.50	-79.91	15:32:11	15:33:11	443.7	349.0	352.6	330.0	-91.1	-19.0	59413	166.[illegible]37	-2.356	84.695	95.305
48	202556004	-4066.70	-67.78	15:44:18	15:45:18	451.6	363.8	351.6	342.7	-100.0	-21.1	50409	66.885	-1.955	84.063	95.937
49	202556049	-4036.20	-67.27	15:44:49	15:45:49	446.1	358.0	346.1	336.9	-100.0	-21.1	50032	-166.878	-1.932	84.031	95.969
50	202556104	-4005.90	-66.77	15:45:19	15:46:19	446.6	366.0	346.2	344.7	-100.4	-21.3	49657	-166.876	-1.916	84.002	95.998
52	202556204	-3945.20	-65.75	15:46:20	15:47:20	440.6	350.5	339.7	328.9	-100.9	-21.6	48907	-' 66.866	-1.865	83.934	96.066
53	202556249	-3914.90	-65.25	15:46:50	15:47:50	466.0	370.9	364.4	349.2	-101.6	-21.7	48532	66.873	-1.854	83.901	96.099
54	202557104	-3399.20	-56.65	15:55:26	15:56:26	439.1	360.4	328.4	336.6	-110.7	-23.8	42155	[illegible]	-1.426	83.245	96.755

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Summary of Inputs for Dactyl Orbit Determination

(Data for Table 1) pg 2

		Time from Reference'		Time		Ida		Ida-2		Delta		Range to	Camera Pointing (EME2000)			North
													RA	DEC	Twist	
Picture	S/C Clock	(sec)	(min)	(UTC)	(ET)	Sample	Line	Sample	Line	Sample	Line	Ida (km)	(deg)	(deg)	(deg)	(deg)
56	**202557204**	**-3338.50**	-55.64	15:56:27	15:57:27	437.4	357.7	325.2	333.7	-112.2	-24.0	41405	-166.793	-1.366	83.152	96.848
58	**202557304**	**-3277.90**	-54.63	15:57:27	15:58:27	442.7	358.3	329.6	334.4	-113.1	-23.9	40656	-166.788	-1.306	83.061	96.939
59	**202557349**	**-3247.50**	-54.13	15:57:58	15:58:58	455.2	373.5	341.7	349.3	-113.5	-24.2	40280	-166.792	-1.282	83.011	96.989
60	**202558304**	**-2671.40**	-44.52	16:07:34	16:08:34	445.3	340.4	316.6	313.3	-128.7	-27.1	33161	-166.681	-0.539	81.885	98.115
62	**202558404**	**-2610.50**	-43.51	16:08:35	16:09:35	458.0	349.6	327.2	322.4	-130.8	-27.2	32409	-166.676	-0.448	87.734	98.266
64	**202558504**	**-2549.90**	-42.50	16:09:35	16:10:35	467.7	348.1	335.3	320.3	-132.4	-27.8	31661	-166.667	-0.347	81.579	98.421
65	**202558549**	**-2519.50**	-41.99	16:10:06	16:11:06	442.0	345.6	308.4	318.1	-133.6	-27.5	31286	-166.645	-0.296	81.501	98.499
66	**202559404**	**-2004.07**	-33.40	16:18:41	16:19:41	444.9	339.5	288.1	308.6	-156.8	-30.9	24927	-166.489	0.819	79.767	100.234
74	**202560604**	**-?275.90**	-21.27	16:30:49	16:31:49	476.4	268.5	256.9	235.2	-219.5	-33.3	15975	-166.060	3.939	74.963	105.037
75	**202560649**	**-?245.73**	-20.76	16:31:19	16:32:19	452.1	262.5 **	228.4	226.4	-223.7	-36.1	15606	-166.016	4,142	74.646	105.39
75	202560704	-1215.20	**-20.25**	16:31:50	16:32:50	487. 1	288.1	258.5	254.8	-228.6	-33.3	15232	-166.009	4.349	**74.318**	105.682
77	202560749	**-1184.90**	-79.75	16:32:20	16:33:20	490.7	270.6	257.5	237.5	-233.2	-33.1	14862	**-165.976**	**4.584**	**73.969**	**106.031**
78	**202561279**	-861.40	-14.36	16:37:44	16:38:44	549.8	192.9	242.9	169.2	-306.9	-23.7	10927	**-165.508**	**7.989**	**68.862**	111.138
80	**202561315**	-844.20	-14.07	16:38:01	16:39:01	545.1	195.1	232.1	172.6	-313.0	-22.5	10719	**-165.470**	**8.234**	**68.477**	111.52:
81	**202561327**	-835.50	-13.93	16:38:10	16:39:10	547.4	204.9	231.9	182.6	-315.5	-22.3	10614	**-165.455**	**8.358**	**68.282**	111.71s
82	**202561340**	-826.90	-13.78	16:38:18	16:39:18	525.9	189.4	207.9	168.1	-318.0	-21.3	10511	-165.420	8.491	68.091	111.909
83	**202561353**	-818.20	.13.64	16:38:27	16:39:27	539.4	205.8	217.9	184.7	-321.5	-21.1	10406	**-165.412**	**8.619**	**67.890**	112.110
99	202561579	-679.40	-11.32	16:40:46	16:41:46	901..6	578.4	519.2	576.0	-382.4	-2.4	8742	**-165.322**	1 1.079	64.580	115.420
119	**202552279**	-254.90	-4.25	16:47:50	16:48:50	N/A	N/A	194.9	220.2	N/A	N/A	3957	**-161.727**	**32.704**	40.169	139.831
148	**202562701**	-3.50	-0.06	16:52:02	16:53:02	N/A	N/A	14.0	455.6	N/A	N/A	2392	**-104.804**	**81.633**	**-29.417**	209.417

EME20001dapole:
RA = 348.76deg
DEC= 87.10deg

● Picture reference time:
08/28193
16:52 :05.0 UTC

"Ida center from I Thomas (jail bars)

Camera pointing and North angle data:
RA, DEC based on Ida coordinates (except #119 from interpolated telemetry and #148 from predicts)
Twist **and** North angle from NAIF (predicts)

North = angle measured clockwise in camera plane from horizontal (3 o'clock) to projection of EME2000 pole
Twist = angle measured counter-clockwise in camera plane from horizontal (9 o'clock) to projection of EME2000 pole

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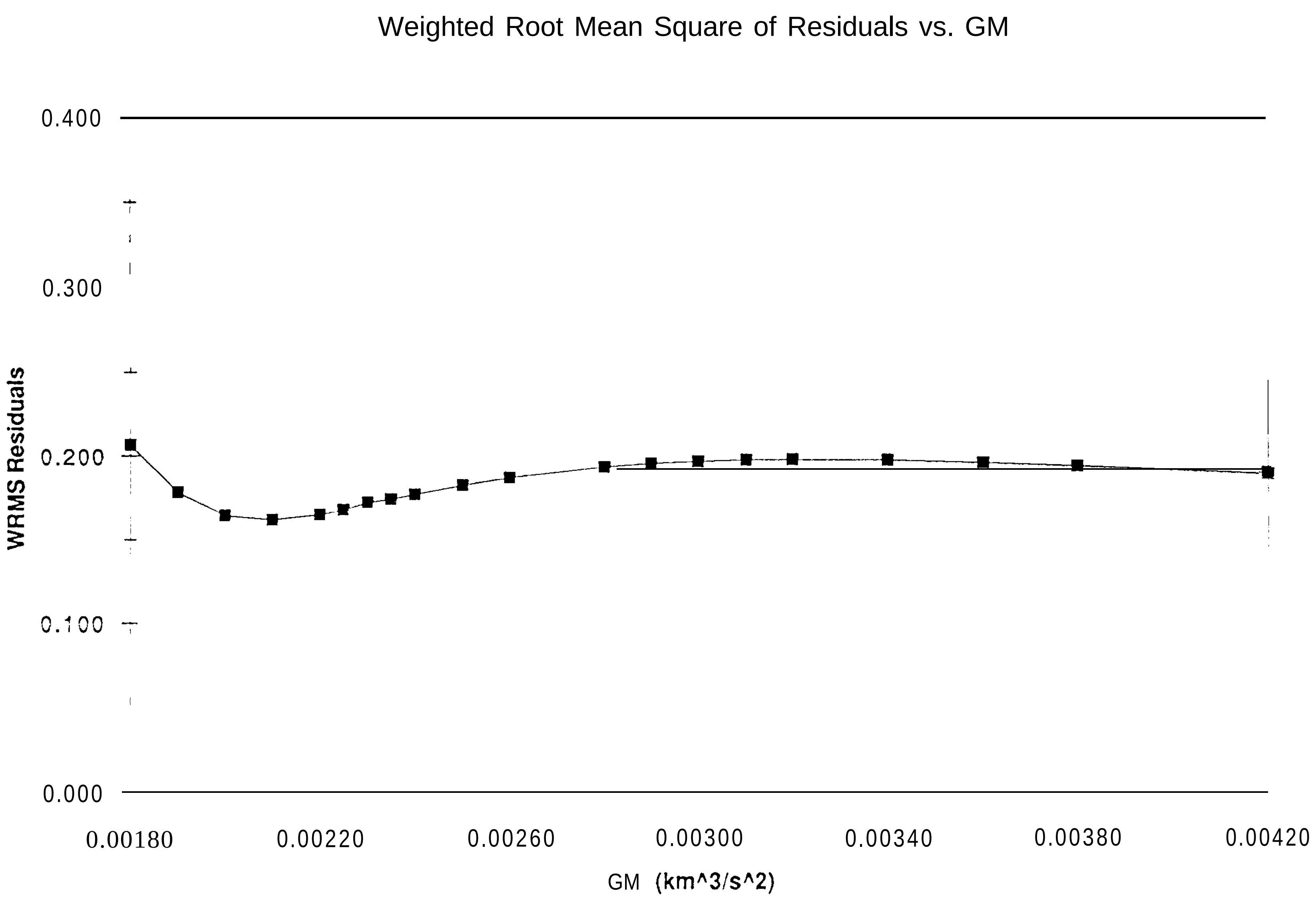
ORBITAL SOLUTIONS

At the start of the analysis, it became clear that a range of mass/density values for Ida would explain the observed positions of Dactyl. To overcome this difficulty, a series of Dactyl orbits were generated for a reasonable range of values for Ida's mass. The range of Ida masses used corresponded to densities from about 1.7 to 3.9 gm/cm^3. Over this range of densities, widely differing orbit solutions resulted, although for each density value there is a unique orbit solution. The formal uncertainties corresponding to a solution for a given Ida mass are small compared to the variation of solutions as a function of mass. As a measure of the accuracy of the solutions, the weighted root-mean-square (WRMS) of the residuals is shown in Figure 1 as a function of the gravitational parameter, GM, where G is the gravitational constant and M is the mass of Ida. Although it is seen that there is a shallow minimum around .0021 km^3/s^2, the variation over the entire range is insignificant.

Table 2 and Figures 2 through 9 show various Dactyl orbital parameters for the different orbital solutions as a function of GM. Using the value of 16,100 km^3 for the volume of Ida as given in Ref. 3, the range of .0018 to .0042 km^3/s^2 for GM corresponds to densities of 1.68 to 3.91 g/cm^3. From these figures it is seen that the angular parameters (inclination, node and argument of latitude) all have small variation over the range and that Dactyl's orbit is nearly in the plane of Ida's equator (i = 1710 to 172°) and in the same direction as Ida's spin (the spin pole is nearly due Ecliptic South). On the other hand, the physical parameters (semi-major axis, eccentricity, periapsis and apoapsis radii) vary quite strongly as a function of GM. Figures 10 and 11 show cross plots of semi-major axis vs. eccentricity and periapsis vs. apoapsis radius respectively, which clearly indicate that the family of solutions as a function of mass (and density) is along a very restricted locus, For Ida densities less than about 2.1 gm/cm^3, the orbits are just barely hyperbolic. For higher Ida densities the orbits are elliptical with a large apoapsis and periapsis around 80-85 km. At a density of about 2.8 gm/cm^3, the orbit is nearly circular (about 82 x 98 km.) For even higher densities the elliptical orbits have apoapses of about 95-100 km, with periapses which decrease with increasing density. For an Ida density greater than about 2.9 gm/cm^3, the closest approach to Ida will be less than about 75 km. Figure 12 shows the orbital geometry for a range of orbit solutions. This view is from the spin pole of Ida, so the motion of Dactyl and the rotation of Ida are both counterclockwise.



Weighted Root Mean Square of Residuals vs. GM
0.400
0.300
0.200
0.100
0.000
WRMS Residuals
0.00180
0.00220
0.00260
0.00300
0.00340
0.00380
0.00420
GM (km^3/s^2)

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TABLE 2

Two-Body Orbital Elements for Dactyl as a Function of Ida's GM ~~Gravitational Parameter~~ - .

(Ida Equatorial Coordinate System[1])

9 2 3 4 6

GM[2] (km³/sec²)	Density[2] (g/cm³)	a[3] (km)	e	i (deg)	Ω (deg)	ω (deg)	f[4] (deg)	(ω+f) (deg)	Period (hrs)	R_o[6] (km)	WRMS[7] (pixels)
0.00180	1.68	39.0	2,77	170.47	-31.26	-27.67	42.04	14.38	-	69.1	0.209
0.00190	1.77	53.1	2.33	170.57	-31.54	-26.69	40.81	14.12	-	70.7	0.181
0.00200	1.86	78.5	1.92	170.68	-31.82	-25.49	39.32	13.83	-	72.5	0.167
0.00210	1.96	132,8	1.56	170.82	-32.10	-24.06	37.60	13.54	-	74,4	0.164
0.00220	2.05	304.1	1.25	170.97	-32.34	-22.42	35.70	13.28	-	76.3	0.168
0.00225	2.10	650.9	1.12	171.04	-32.44	-21.54	34.71	13.17	-	77.2	0.170
0.00230	2.14	7912'0	0.99	171.12	-32.54	-20.51	33.56	13.06	25612.0	78.1	0.174
0.00235	2.19	66:o-	0.88	171.19	-32.63	-19.50	32.47	12.97	620.2	79.0	0.177
0.00240	2.24	355.4	0.78	171.27	-32.71	-18.29	31.16	12.87	238.7	79.8	0.180
0.00250	2.33	200.8	0.59	171.41	-32.85-	-15.52	28.23	12.71	99.3	81.4	0.185
0.00260	2.42	148.8	0.44	171.56	-32.97	-11.87	24.46	12.58	62.2	82.9	0.190
0.00280	2.61	107.7	0.21	171.84	-33.13	2.54	9.85	12.39	36.9	85.0	0.197
0.00290	2.70	97.6	0.13	171.97	-33.19	21.41	-9.09	12.32	31.3	85.1	0.199
0.00300	2.79	90.5	0.09	172.10	-33.24	63.56	-51.30	12.27	27.5	82.7	0.200
0.00310	2.89	85.4	0.11	172.23	-33.28	107.67	-95.44	12.23	24.7	76.1	0.201
0.00320	2.98	81.4	0.16	172.36	-33.30	127.84	-115.64	12.20	22.7	68.6	0.201
0.00340	3.17	76.0	0.26	172.61	-33.33	142.68	-130.50	12.17	19.8	56.2	0.201
0.00360	3.35	72.4	0.35	172.85	-33.32	148.77	-136.59	12.18	17.9	47.2	0.199
0.00380	3.54	70.1	0.42	173.09	-33.28	152.36	-140.14	12.22	16.6	40.5	0.197
0.03420	3.91	67.4	0.54	173.57	-33.12	156.87	-144.49	12.38	14.9	31,1	0,192

[1] Ida pole (IAU convention) RA=348° .76, DEC=87° .10 (Davies *et al.*, 1995); [2] ~~Gravitational parameter;~~ [2] Ida's bulk density based on a volume of 16,100 km³ (Thomas *et al.*, 1995); [3] Semi-major axis positive for hyperbolae; [4] True anomaly at epoch 1993 Aug. 28 16:52:04.7 UTC; [6] Periapse distance; [7] Weighted root mean square of the residuals in the image plane.

listed as

1993-AUG-28 16:52:04.7

5 Argument of latitude

Dactyl Orbit Parameters vs. GM

47 Pictures

(Ida Equatorial Coordinate System*)

(Data for Table 2)

GM (km^3/s^2)	Density# (gm/cm^3)	a ** (km)	e	i (deg)	Ω (deg)	ω (deg)	f (deg)	w + f (deg)	P (hrs)	Rp (km)	Ra (km)	WRMS (pixels)
0.00180	1.68	39.03	2.7691	170.471	-31.262	-27.669	42.044	14.38		69.1		0.209
0.00190	1.77	53.07	2.3312	170.565	-31.537	-26.692	40.808	14.12		70.7		0.181
0.00200	1.86	78.51	1.9229	170.683	-31.823	-25.488	39.317	13.83		72.5		0.167
0.00210	1.96	132.75	1.5602	170.819	-32.096	-24.060	37.604	13.54		74.4		0.164
0.00220	2.05	304.06	1.2508	170.966	-32.336	-22.417	35.701	13.28		76.3		0.168
0.00225	2.10	650.89	1.1186	171.038	-32.440	-21.539	34.711	13.17		77.2		0.170
0.00230	2.14	7912.00	0.9901	171.117	-32.542	-20.507	33.564	13.06	25612.0	78.1	15745.9	0.174
0.00235	2.19	667.00	0.8816	171.188	-32.627	-19.504	32.469	12.97	620.2	79.0	1255.1	0.177
0.00240	2.24	355.44	0.7754	171.266	-32.711	-18.293	31.161	12.87	238.7	79.8	631.1	0.180
0.00250	2.33	200.77	0.5944	171.414	-32.851	-15.524	28.234	12.71	99.30	81.4	320.1	0.185
0.00260	2.42	148.84	0.4432	171.559	-32.965	-11.874	24.455	12.58	62.2	82.9	214.8	0.190
0.00280	2.61	107.67	0.2104	71.837	-33.133	2.544	9.846	12.39	36.9	85.0	130.3	0.197
0.00290	2.70	97.60	0.1280	71.971	-33.193	21.410	-9.087	12.32	31.3	85.1	110.1	0.199
0.00300	2.79	90.54	0.0868	72.102	-33.240	63.564	-51.295	12.27	27.5	82.7	98.4	0.200
0.00310	2.89	85.36	0.1086	72.231	-33.276	107.665	-95.436	12.23	24.7	76.1	94.6	0.201
0.00320	2.98	81.43	0.1582	72.358	-33.301	127.837	-115.637	12.20	22.7	68.6	94.3	0.201
0.00340	3.17	75.96	0.2604	72.607	-33.325	142.675	-130.503	12.17	19.8	56.2	95.7	0.201
0.00360	3.35	72.43	0.3485	72.851	-33.316	148.772	-136.592	12.18	17.9	47.2	97.7	0.199
0.00380	3.54	70.07	0.4226	173.091	-33.278	152.357	-140.139	12.22	16.6	40.5	99.7	0.197
0.00420	3.91	67.37	0.5385	173.566	-33.119	156.873	-144.489	12.38	14.9	31.1	103.7	0.192

Epoch = 8/28/93 16:52:04.66 UTC (16:53:04.84 ET)

*Ida pole (IAU convention): RA=348.76 deg, DEC=87.10 deg in EME2000

**Positive for hyperbola

#Assumes Ida volume = 16,100 km^3

WRMS = weighted root mean square of residuals

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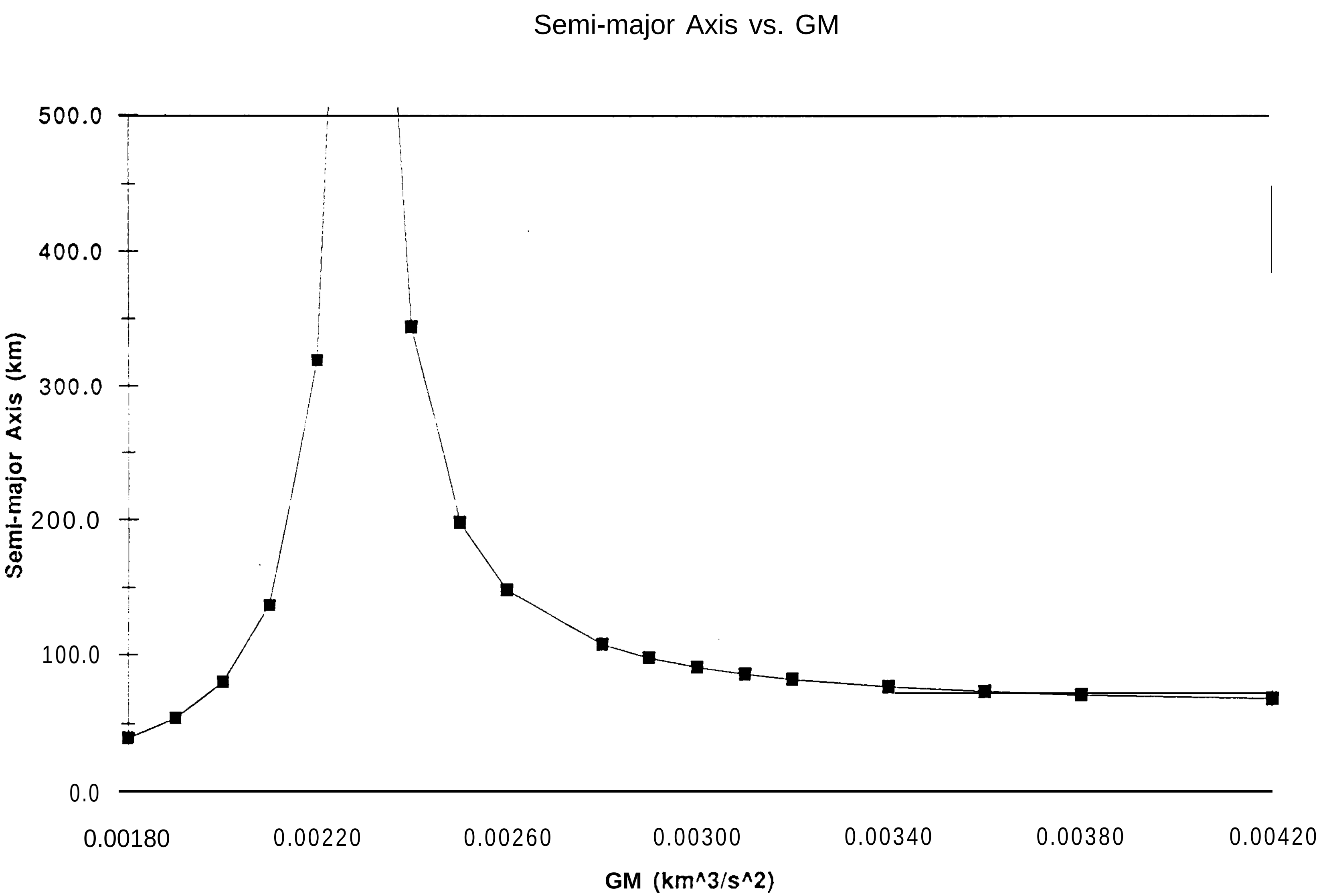
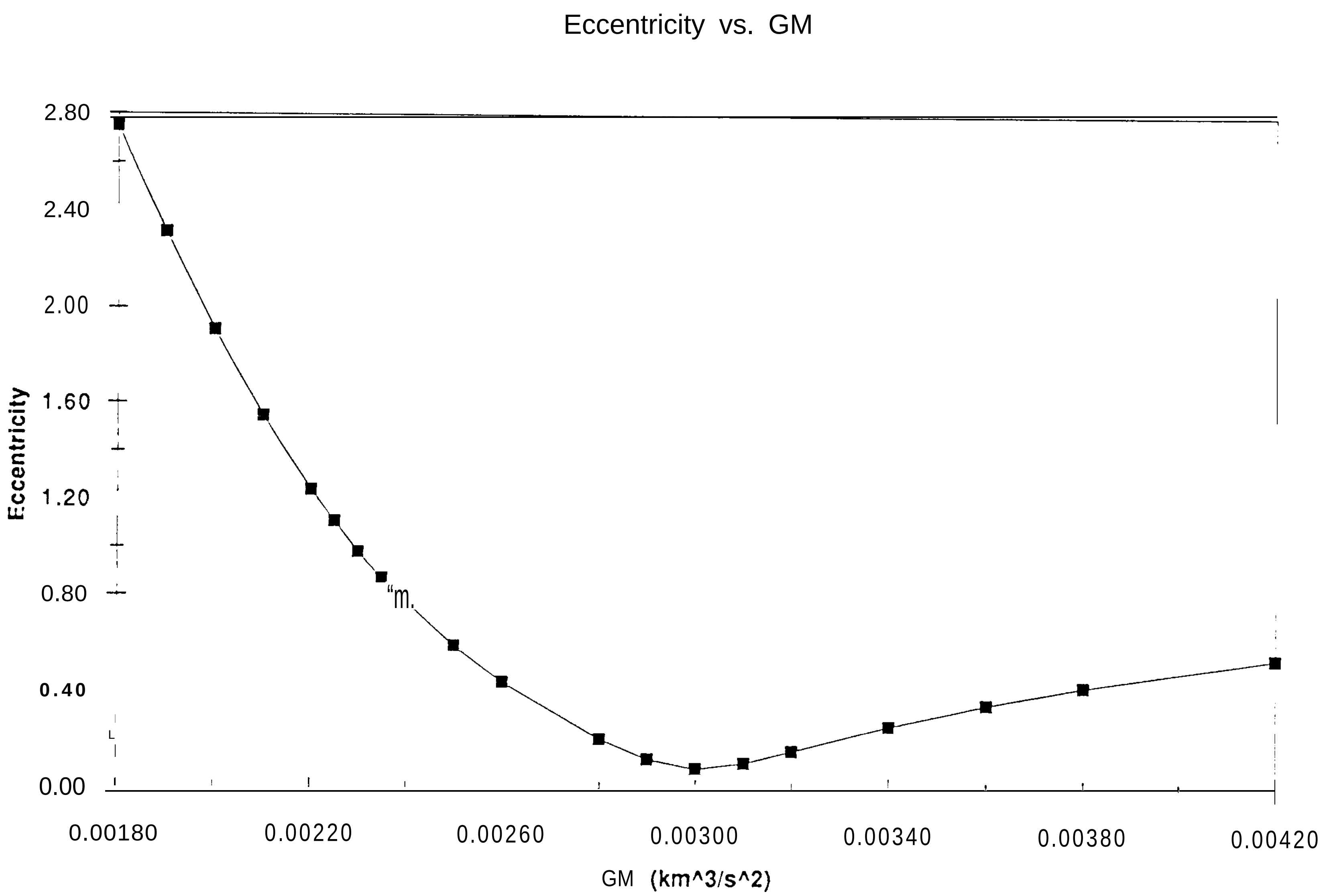


Semi-major Axis vs. GM
500.0
400.0
300.0
200.0
100.0
0.0
Semi-major Axis (km)
0.00180
0.00220
0.00260
0.00300
0.00340
0.00380
0.00420
GM (km^3/s^2)

LAD 8/30/94



Eccentricity vs. GM
2.80
2.40
2.00
1.60
1.20
0.80
0.40
0.00
Eccentricity
0.00180
0.00220
0.00260
0.00300
0.00340
0.00380
0.00420
GM (km^3/s^2)

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Fig 4

Periapse Radius vs. GM

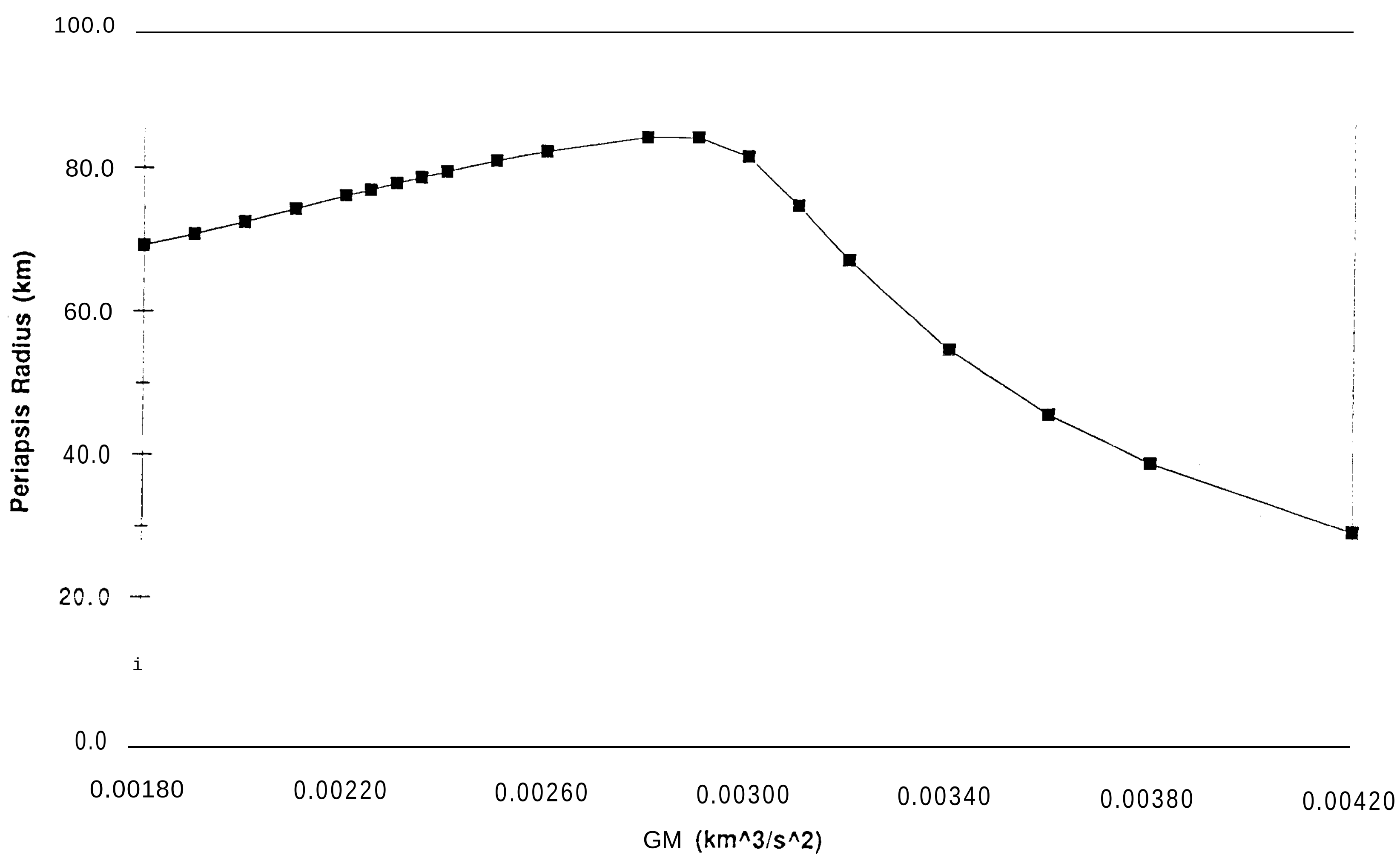

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Fig 5

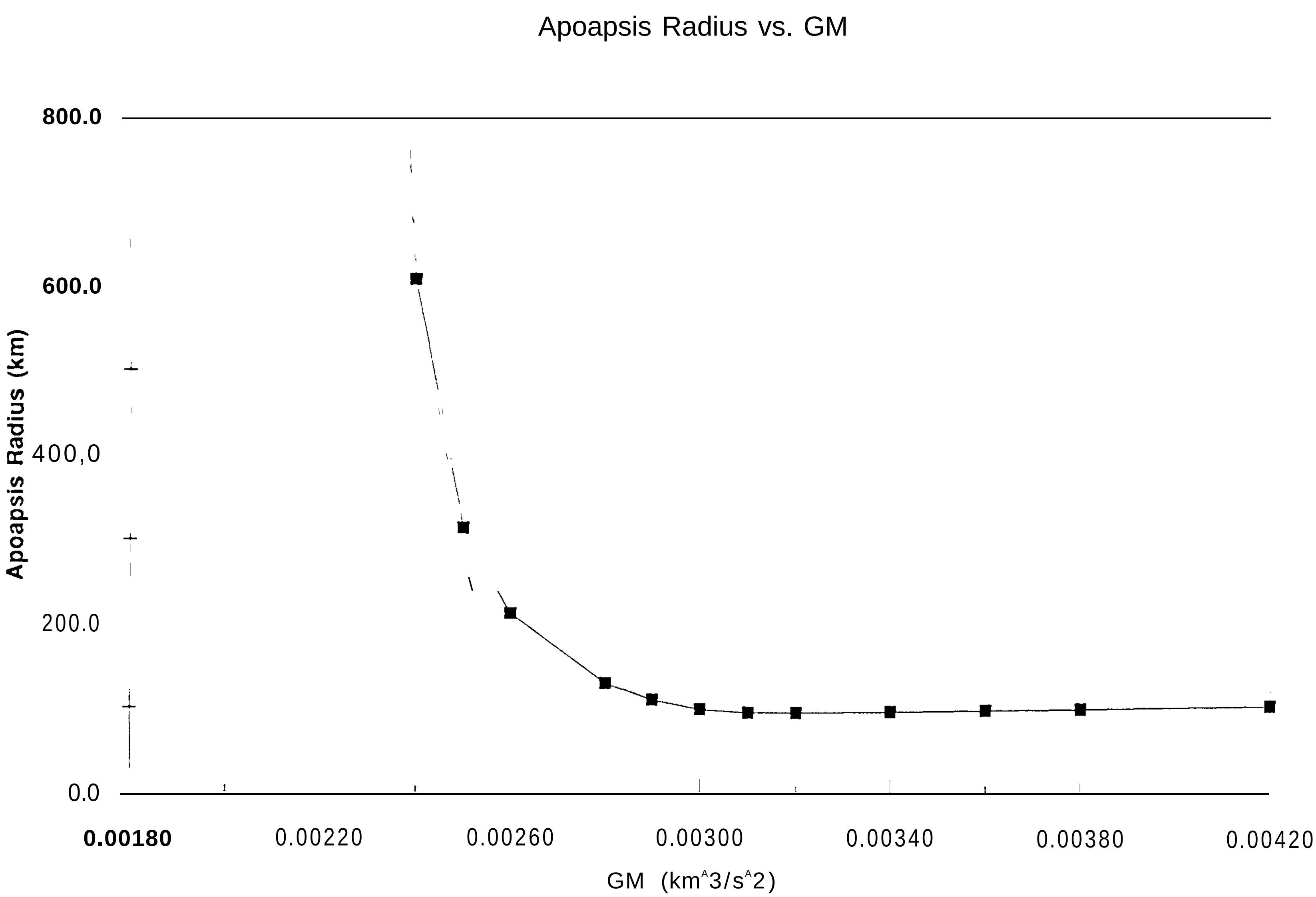

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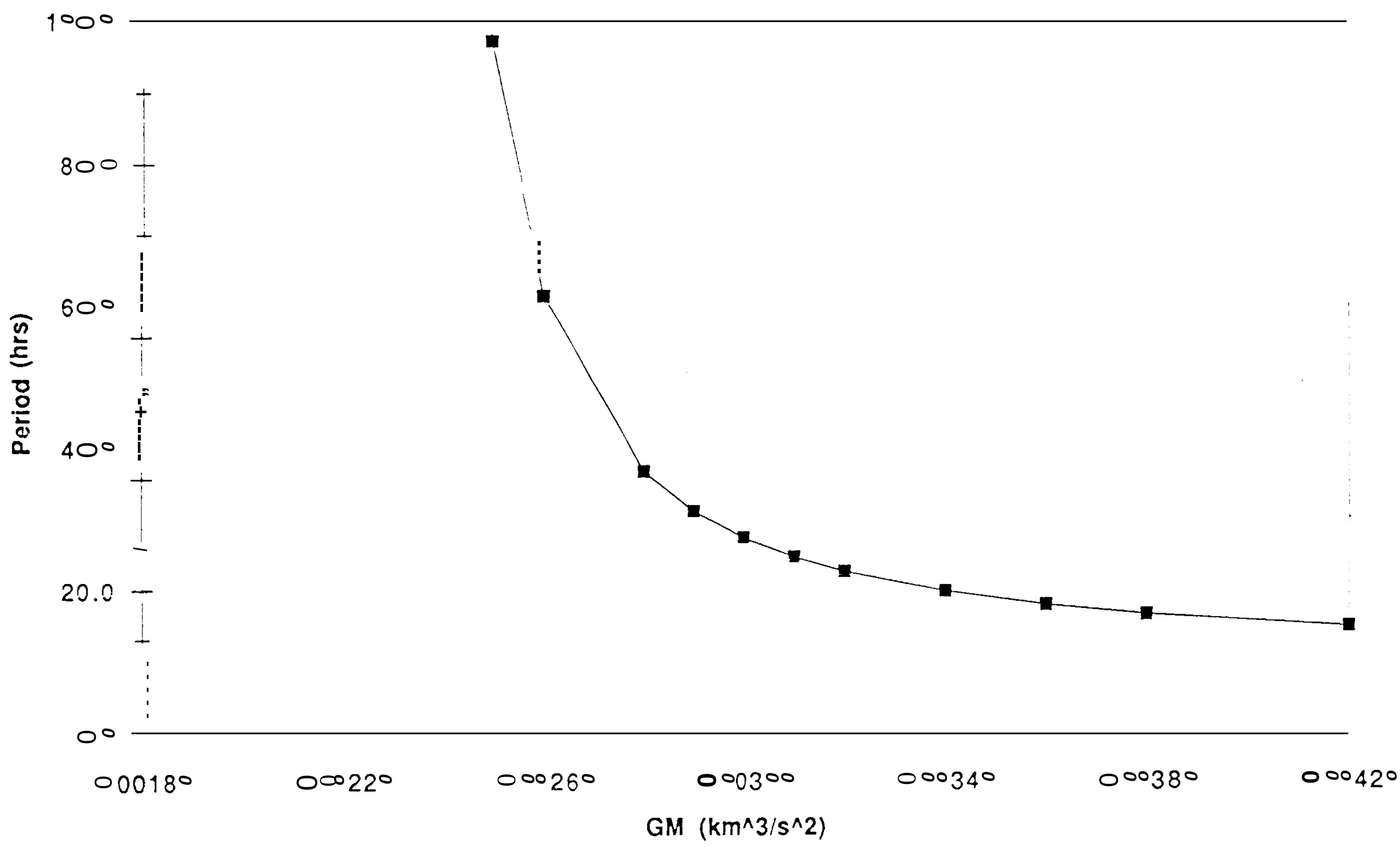
Fig 5

Period vs. GM



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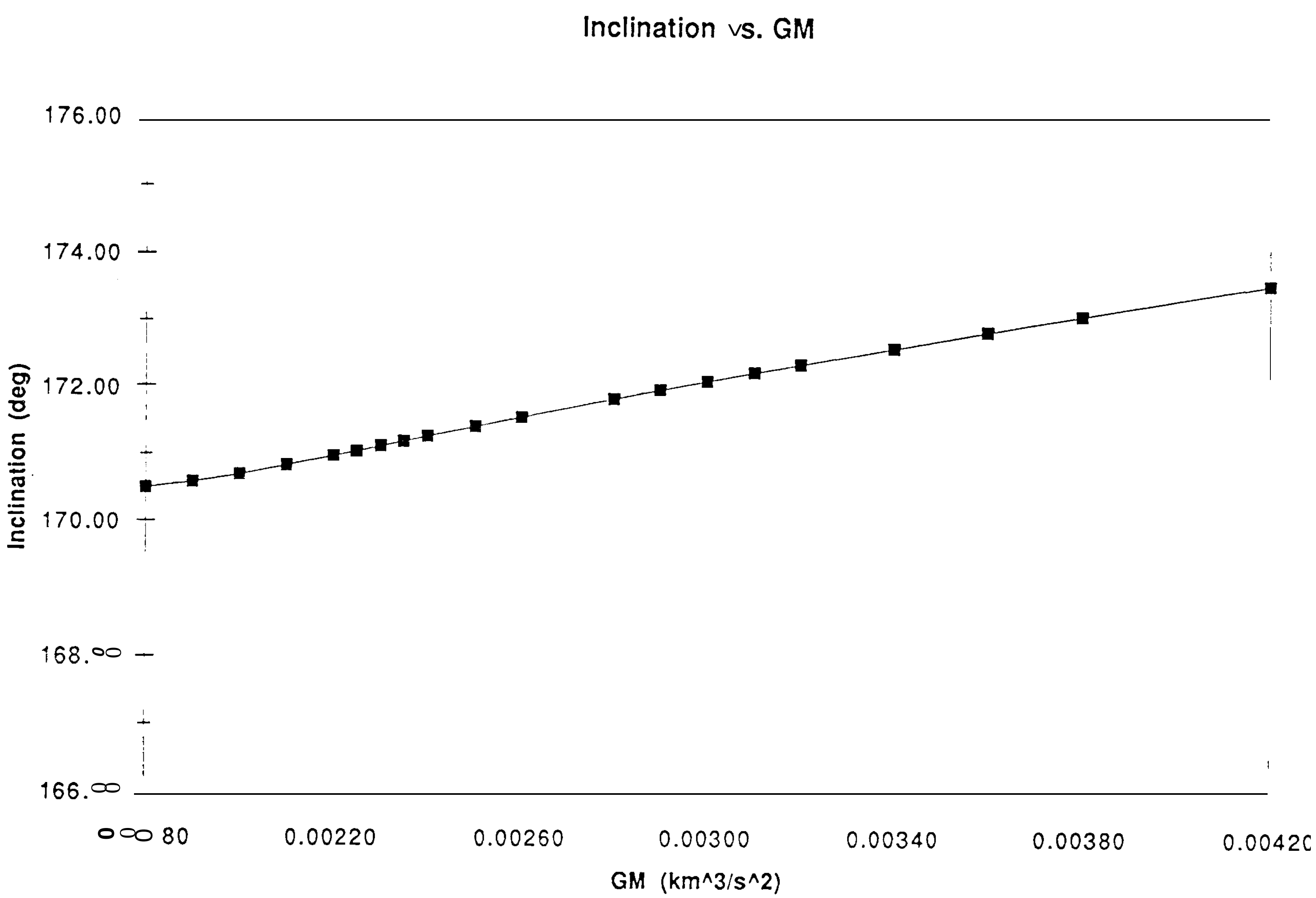
1.7



Inclination vs. GM
176.00
174.00
172.00
170.00
168.00
166.00
Inclination (deg)
0.00180
0.00220
0.00260
0.00300
0.00340
0.00380
0.00420
GM (km^3/s^2)

Ascending Node vs. GM

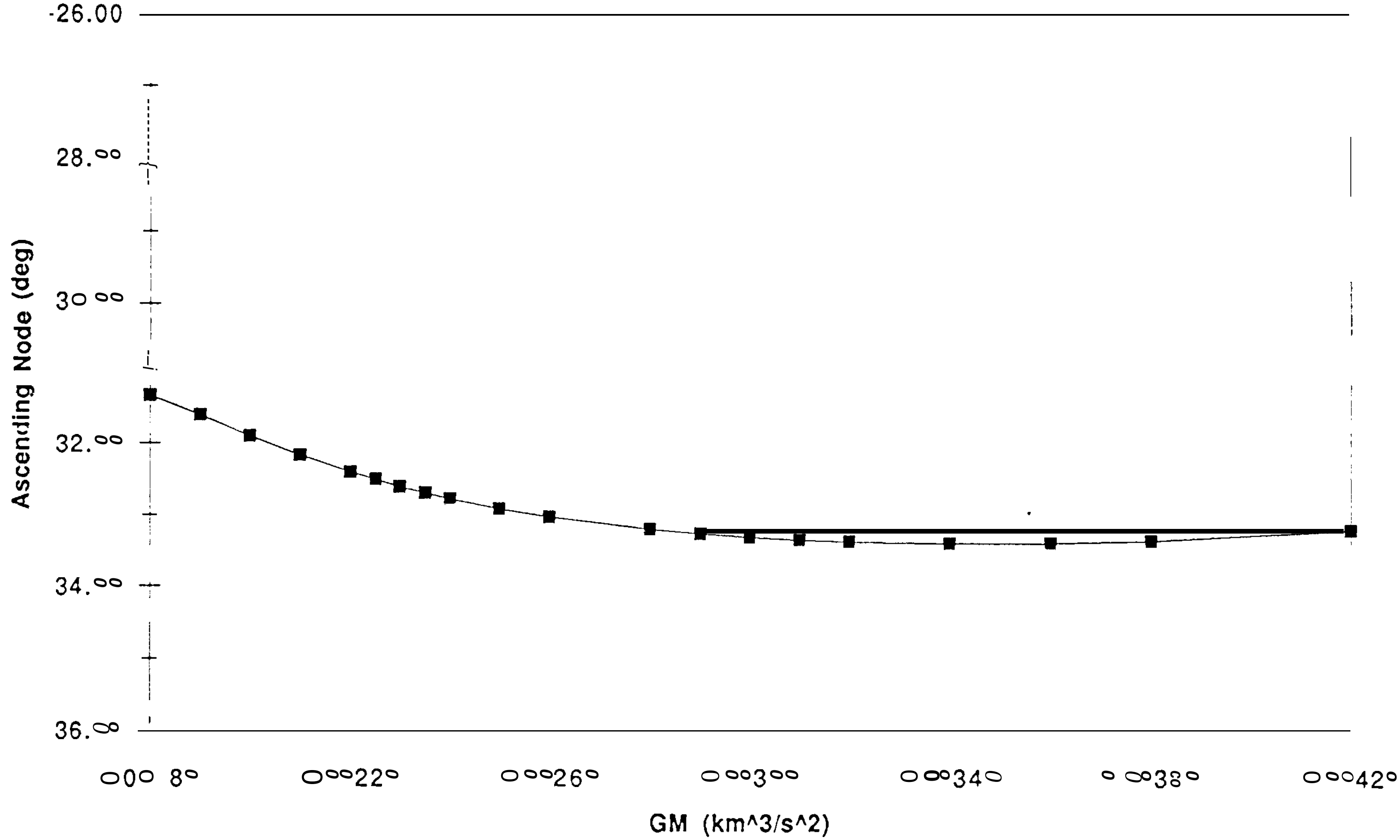


Fig 7

Argument of Latitude (at Epoch) vs. GM

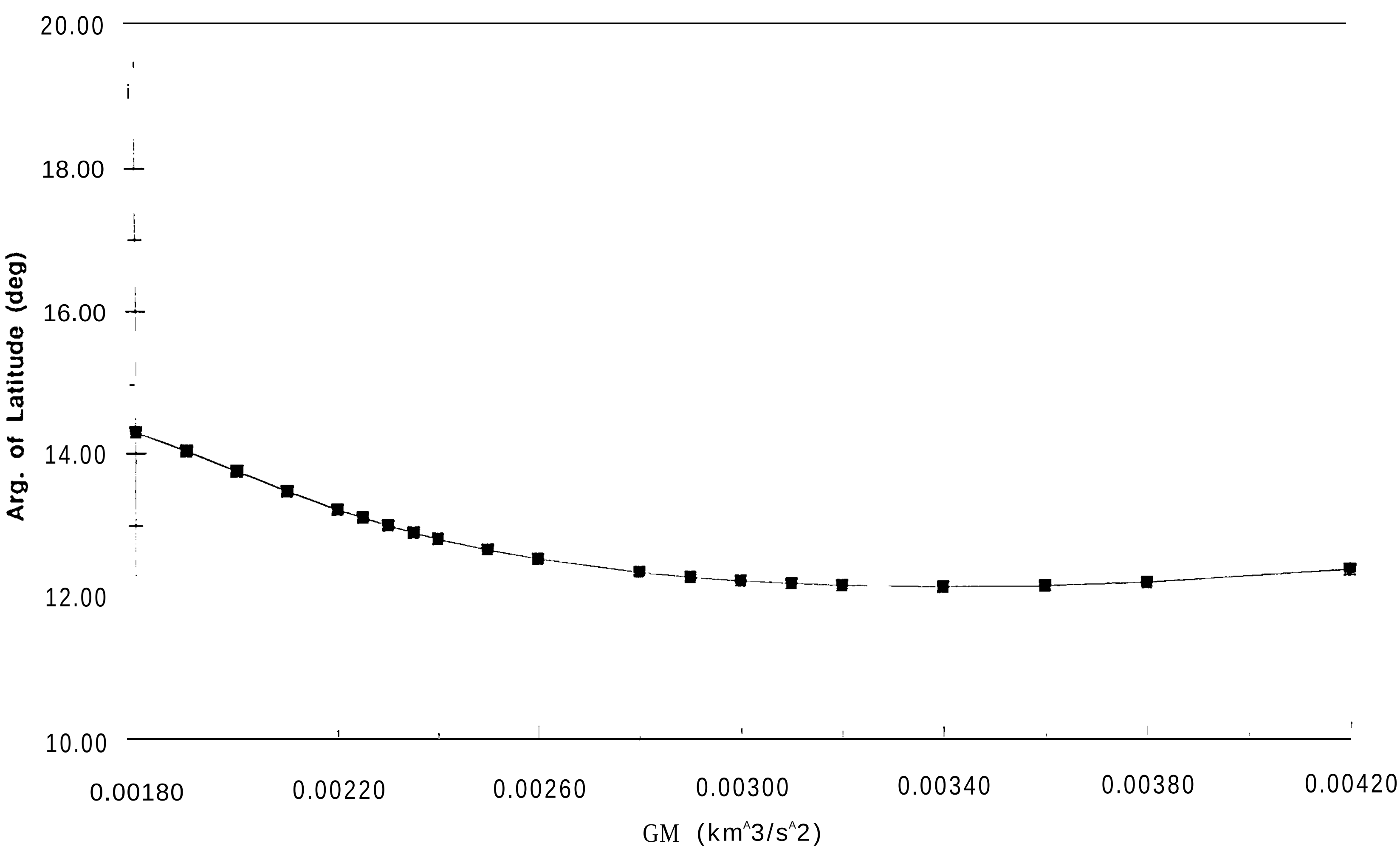


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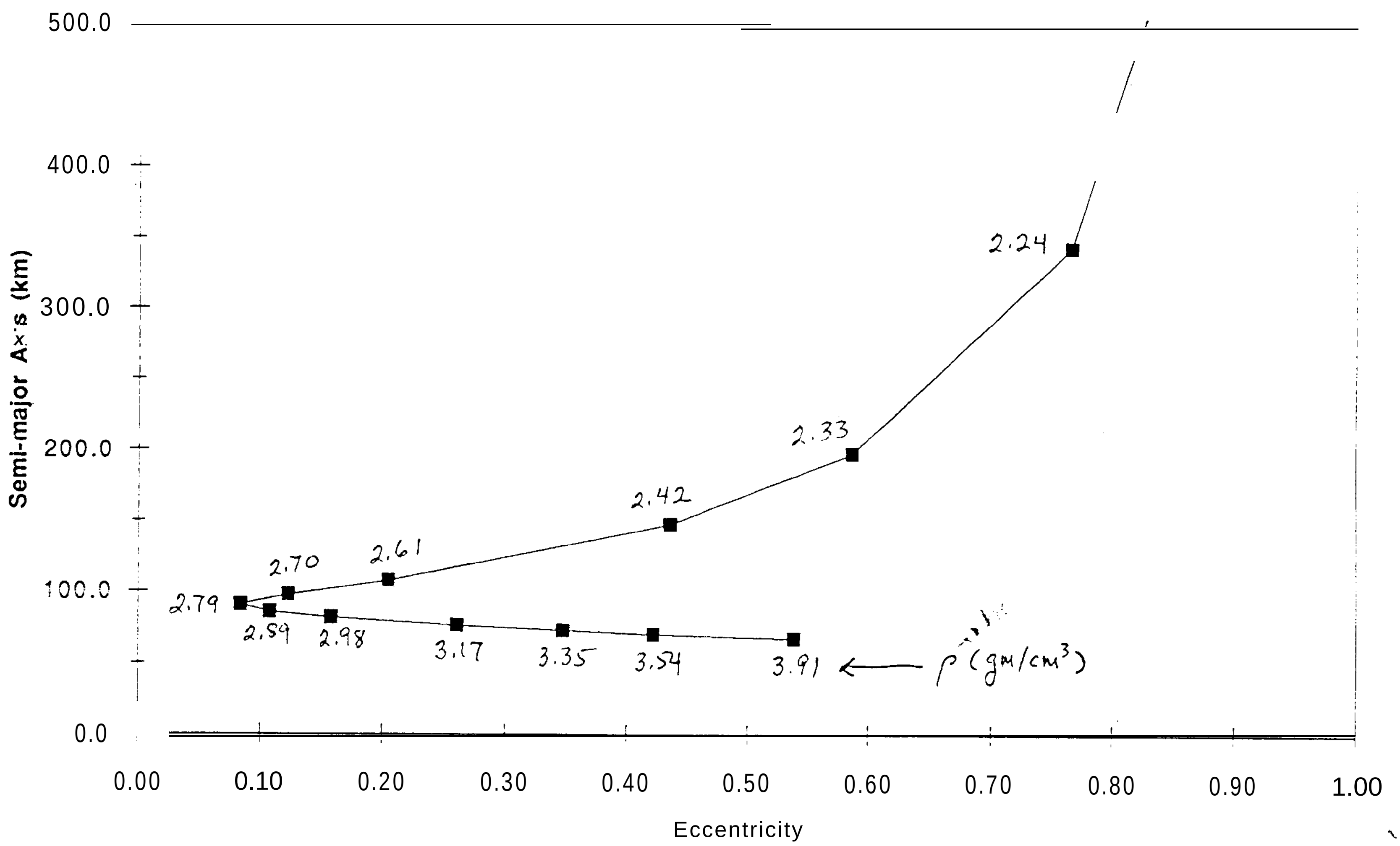
Fig 10

Semi-major Axis vs. Eccentricity



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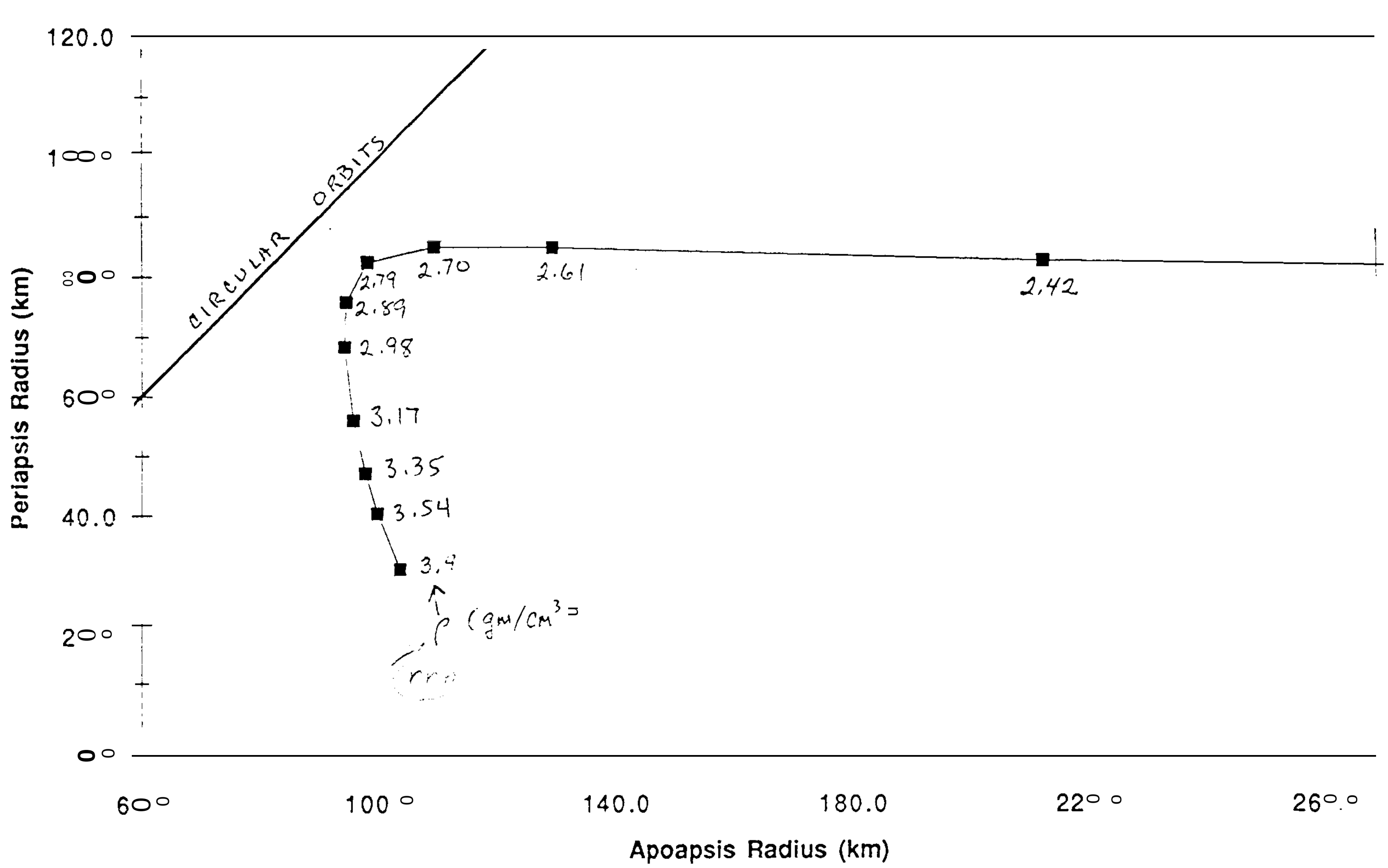
Periapse Rad us vs. Apoapsis Radius



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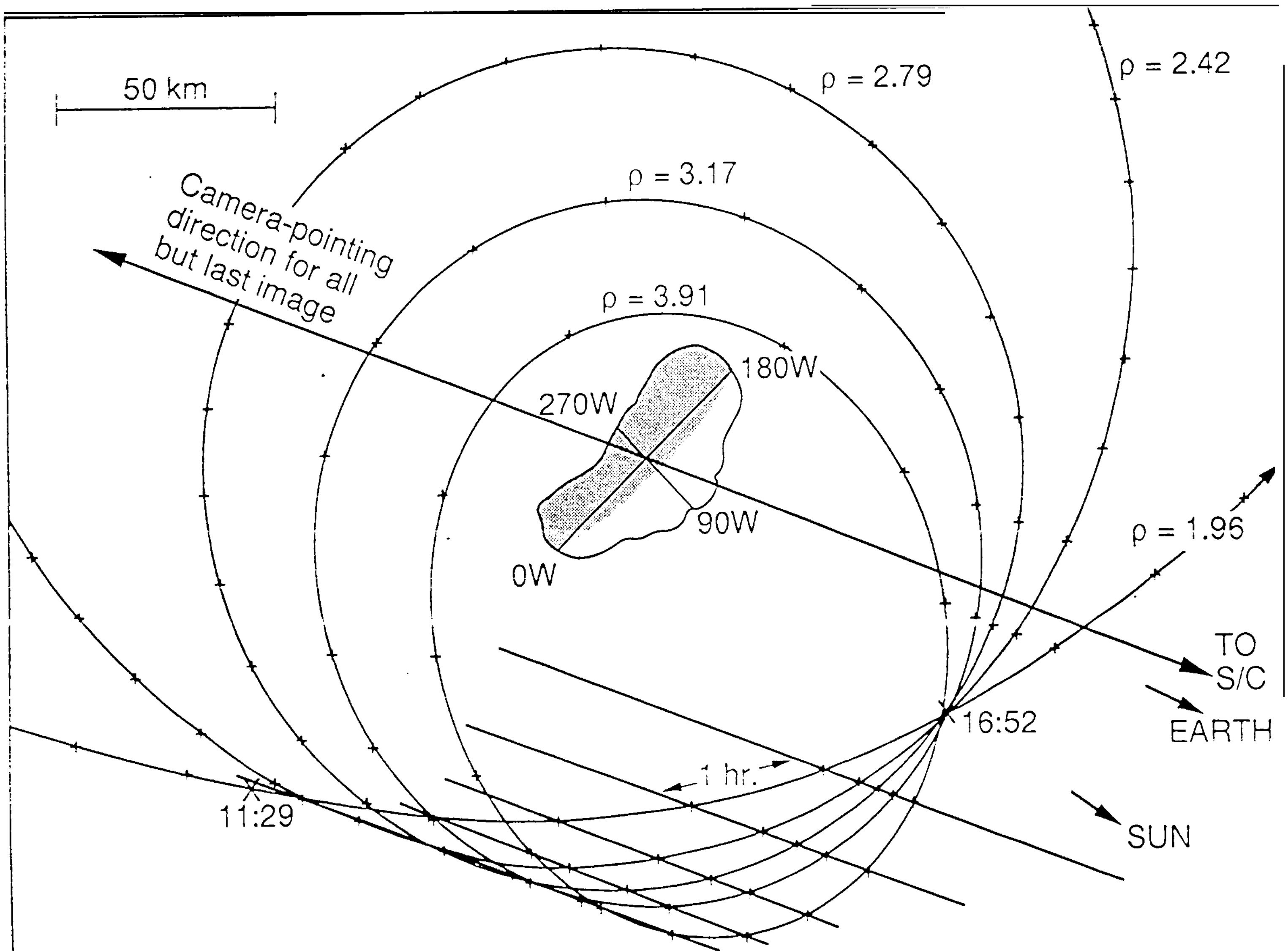

Notes:
. Ida rotates in 4.63 hours
• ρ = Density

• Ida is shown oriented as it was at 16:52:05 (UTC) on Aug. 28, 1993

Figure 12 shows that when points at the same epoch on each possible Dactyl orbit arc connected, they are seen to fall along straight 1 ines parallel to the line through the center of Ida that points to the spacecraft. All of the images but the very last were taken when Galileo was several thousand to several hundred thousand kilometers from Ida and nearly in its equatorial plane, so Galileo was viewing the Ida/Dactyl system from far down to the right in the figure. For scale, the long axis of Ida is 58 km and the orientation shown is at the time of Galileo's closest approach. Thus, the area of the figure only covers a few hundred kilometers around Ida. The final image mosaic was taken very near to Galileo's closest approach to Ida and included parts of both Ida and Dactyl in separate images. At that point, Galileo was essentially looking down on the Dactyl orbit plane (essentially the plane of the figure) and Dactyl was at the point where all of the possible orbits cross. The lowest of the parallel lines connects the points on each orbit at five hours prior to closest approach, or about the time of the earliest image. Since Dactyl was viewed for only a fraction of its orbit and from a nearly edge-on vantage point, all of the orbits shown fit the observations equally well. If one imagines being on the Galileo spacecraft looking at Ida and Dactyl, then all of (he orbit solutions appear the same during the five hour approach, since the differences between them arc all along the line of sight (the parallel lines in the figure.)

DYNAMICAL ANI) STATISTICAL CONSTRAINTS

For a given nlass/density of Ida a unique and well determined two-body orbit can be found, but this dots not in and of itself allow one to determine the density of Ida. Only the application of the dynamics of motion about a non-spherical body and knowledge of the general distribution of asteroidal material in the entire asteroid belt can reduce the range of possible n~ass/density values for Ida.

Orbits which come closer than about 75 km to Ida are unstable and either collide with Ida or escape (Ref. 2). It can then be concluded that the orbit solutions which correspond to an Ida density of about 2.9 gm/cm^3 or greater are not physi tally possible. At the other extreme, hyperbolic and even highly elliptical orbits around Ida are very unlikely. The observed speed of Dactyl with respect to Ida for *any* of the orbit **solutions is no more than about 10** m/s and is typically -6 m/s, about the speed of a fast run or a slowly thrown baseball. The chance of a random piece of asteroidal material the size of Dact yl passing by Ida at that speed just when Galileo was observing it is $\leq 2x10^{-17}$ (Ref. 1). In addition, if Dactyl were in a hyperbolic or highly elliptical orbit, it would have been seen in Hubble observations taken over an eight hour period about seven months after the Galileo flyby (Ref. 1). These observations could have easily seen Dactyl had it been more than about 700 km from Ida. Combining these two restrictions gives a preliminary estimate of the density of Ida for the assumed volume of 16,100 km^3 in the range of 2.1 to 2.9 gm/cm^3. Allowing for the uncertainty in the modeled volume of Ida increases the range to 2.0 to 3.1 gm/cm^3. This somewhat surprisingly low density range suggests that Ida is made of fairly light rocks. This is contrary to what was expected of S-Type asteroids. Alternatively, and perhaps in addition, Ida may be fairly porous, similar to a pile of sand and rock. A discussion of the significance of this result is given in Ref. 2.

SUMMARY AND CONCLUSIONS

The encounter of the Galileo spacecraft with the asteroid 243 Ida has yielded the discovery of the first asteroid satellite, Dactyl. A range of solutions for the orbit of Dactyl as a function of the mass of Ida fit the observational data, but only those orbits corresponding to densities in the range of 2.0 to 3.1 gm/cm^3 are likely candidates. Dactyl's orbit is nearly in the plane of Ida's equator ($i \approx 171°$ to $172°$) and in the same direction as Ida's spin.

Since perturbations due to the gravitational potential of Ida's irregular shape and the gravitational influence of the Sun must have a long term effect on the orbit of Dactyl, further work on the long term stability of orbits which fit the observations, as well as a more precise analysis of the SS1 images themselves may lead to a better determination of both the orbit of Dactyl and the density of Ida.

ACKNOWLEDGMENT

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2. M. J. S. Belton, C. R. Chapman, P. C. Thomas, M. E. Davies, R. Greenberg, K. Klaasen, D. Byrnes, L. D'Amario, S. Synnott, T. V. Johnson, A. McEwen, W. J. Merline, D. R. Davis, J-M. Petit, A. Storrs, J. Veverka, and B. Zellner, "Bulk density of asteroid 243 Ida from the orbit of its satellite Dactyl, " *Nature* v. 374, 27 April 1995.

3. P. C. Thomas, J. Veverka, M. J. S. Belton, C. R. Chapman, M. E. Davies and R. Sullivan, "The Shape of Ida," submitted to *Icarus*, in press.